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EFFECT OF TIDAL CHANGES ON PHYSICAL, CHEMICAL, AND BIOLOGICAL CONDITIONS IN THE SEA WATER OF THE SAN DIEGO REGION

BY

ERIK G. MOBERG AND WINFRED EMORY ALLEN

BULLETIN OF THE SCRIPPS INSTITUTION OF OCEANOGRAPHY
LA JOLLA, CALIFORNIA

TECHNICAL SERIES, Volume 1, No. 1, pp. 1–17, 4 figures in text

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY, CALIFORNIA
1927

The SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA, CALIFORNIA, announces the beginning of a new series of its **Bulletin**—the **Technical Series.** The following numbers have been issued. Other numbers are in preparation.

Earlier papers from the Institution have appeared as **Bulletins of the Scripps Institution for Biological Research,** and as contributions to the series, **University of California Publications in Zoology.**

BULLETIN OF THE SCRIPPS INSTITUTION OF OCEANOGRAPHY, TECHNICAL SERIES.—Edited by T. Wayland Vaughan and F. B. Sumner.

Volume 1. 1927–

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PUBLISHED BY THE
UNIVERSITY OF CALIFORNIA PRESS
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I. Observations on the Effect of Tidal Changes on Physical and Chemical Conditions of Sea Water in the San Diego Region

BY

ERIK G. MOBERG

II. Half-hourly Collections of Marine Microplankton Taken at the Scripps Institution Pier in 1923

BY

WINFRED EMORY ALLEN

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Issued March 30, 1927

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY, CALIFORNIA

CAMBRIDGE UNIVERSITY PRESS
LONDON, ENGLAND

I. OBSERVATIONS ON THE EFFECT OF TIDAL CHANGES ON PHYSICAL AND CHEMICAL CONDITIONS OF SEA WATER IN THE SAN DIEGO REGION

BY

ERIK G. MOBERG

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INTRODUCTION

A series of hydrographic observations and plankton catches taken at the entrance to Mission Bay, in November, 1922, gave interesting information concerning the effect of tidal changes upon oceanographic conditions in that locality. Since the topographic features of Mission Bay are rather unique, similar studies were undertaken at the Scripps Institution pier in order to determine whether tidal movements along the open coast produce effects analogous to those produced in the bay. A knowledge of the changes in physical, chemical, and biological conditions accompanying changes in tide is of especial importance since much of the material used by the Scripps Institution in oceanographic studies is obtained from points near shore.

In the present paper are recorded the results of two series of collections from Mission Bay and three from the Scripps Institution pier. In two of the series from the pier, temperatures and water samples were taken from the bottom as well as from the surface; and in one series from the pier, quantitative plankton catches were obtained. The results of one of the Mission Bay series have been discussed elsewhere (Allen, 1923), particularly with respect to the biological studies, but the temperature and chemical data are included in the present paper for purposes of comparison.

LOCAL TOPOGRAPHY

The Scripps Institution, from the pier of which most of these collections were made, is located about twelve miles north of Point Loma and about one and a quarter miles northeast of the southern end of an open embayment about five miles across from north to south. McEwen (1916, pl. 2) has used the appropriate designation "La Jolla Bay" for this body of water. Its southern boundary consists of rocky cliffs extending sharply westward for about half a mile, thus giving a more typically bay-like appearance to the southern portion. The eastern shore for a mile north from the southern end is low and fronted by a sandy beach, most of which, through action of tide and current, may sometimes be swept clean to underlying rock or at other times be piled high with gravel and cobblestones. At the north end of this beach the pier extends west directly seaward a thousand feet without obstruction. North of the pier the eastern shore of the embayment is a series of cliffs composed of sandstone and clay with more or less discontinuous sandy beaches exposed at their bases. Trending in a northwesterly direction from the southeastern angle of the bay is a submerged ravine which ranges up to about two hundred and seventy meters in depth. But, in the main, the depth at about one thousand feet from the eastern shore line to a point just north of the pier is not far from six meters. About one thousand feet north of the pier is a submerged ravine trending south of west in which depths range to one hundred meters or more. Farther away from the pier in all seaward directions alternating ridges and depressions give marked diversities in depth within moderate distances from shore. Thus it appears that the pier is situated near the northern border of a small shallow shelf surrounded by steep submerged slopes. Local experience has shown that currents sweeping across this shelf may at times make a temporary change of nearly a meter in depth of water at any given place by shifting the bottom sediment. Whatever may be true of other places, it is evident that local bottom topography increases the complexity and adds to the difficulty of interpreting both hydrographic and biological conditions.

The entrance to Mission (or False) Bay is, in a straight line, about six miles south of the Scripps Institution. At high tide the bay occupies an area of about four square miles but at low tide it is reduced to channels and lagoons of less than half that extent. Since the average depth at high tide is probably not more than about one meter, a considerable portion of the water is exchanged at each tidal

cycle. The entrance to the bay is narrow, consequently the tidal flow is rapid. As no water enters the bay by run-off from the land except during the rainy season, there had been no addition of fresh water for a period of several months prior to making these collections.

METHODS

In series A, B, and C water samples were drawn up by means of an ordinary bucket into which a thermometer was immediately inserted and temperature readings taken. Some of the water was then transferred to bottles which were tightly stoppered and stored away from light until the conclusion of the series, when they were brought to the laboratory for hydrogen ion and salinity determinations. In series D and E water samples were taken with an Ekman sampling bottle and to it were attached reversing thermometers for obtaining temperature readings. Some of the water was drawn directly from the Ekman bottle into the H-ion apparatus and the remainder stored in bottles for salinity determinations.

Hydrogen ion concentration was determined colorimetrically (cresol red being used as indicator) by means of an apparatus essentially similar to the one described by Barnett and Barnett (1920). Artificial light was used throughout, thus making it possible to obtain readings at night as well as during the day. The H-ion concentrations of the samples of the last two series were determined immediately upon collection, but with the first three series, not until after they had been stored for from one to about twenty-four hours. Numerous experiments have shown, however, that, provided certain precautions are taken, water samples may stand for several days without any measurable effect on the hydrogen ion content being produced. The H-ion values have not been corrected for the salt effect but over the range of salinity found the correction is constant and the values are therefore comparable. The results are expressed as pH and are accurate to about pH 0.01.

Salinities were determined according to the usual method employed by the Scripps Institution (Cummings, 1921) and are accurate to about 0.05 $^{o}/_{oo}$.

By means of an apparatus invented and constructed by Mr. James Ross of the Scripps Institution, a continuous automatic record of certain drift currents was obtained during the periods when series D and E were collected. This apparatus is designed to record the direction and velocity of currents flowing parallel to the coast, i.e., in a north or south direction only; in the case of currents flowing at an angle to the coast only the north or south component is measured.

DISCUSSION OF RESULTS

These series of collections were planned mainly for the purpose of determining the effect of tidal changes upon certain physical and chemical conditions of the water. In interpreting the results, however, it is necessary to take into account several other factors, many of which are independent of tidal movements. Such independent factors are, for example, climatic conditions, diurnal changes, and certain vertical and horizontal currents. Owing to the necessity of giving some attention to all these factors, some of which could not be accurately measured, and to possible interaction of the conditions studied, the data obtained were not considered adequate for statistical treatment and the results are shown in graphs.

Series A and B

Series A and B were collected from Mission Bay on November 3 and 4, 1922. Series A was taken in the channel near the entrance to the bay at half-hour intervals, beginning at 8:45 P.M. on November 3 and continuing until 5:15 P.M. on November 4. Series B was taken at the same time as series A, but with less regularity, in the shallower water about a mile farther inside the bay. During the entire period the sky was clear, the wind light, and the temperature of the air relatively low, the maximum and minimum temperature on November 3 being respectively 63° and 45° F., and on November 4, 63° and 45° F. The results of both series are shown in figure 1.

The curves show that there was a close similarity between the two series in regard to fluctuations of all the conditions studied and that the fluctuations of series B, which was taken in shallower water, were more marked. During the night ebbing tide produced a fall in temperature and pH and a rise in salinity, whereas during the day it produced no change except in salinity. The series included only one flowing tide (at night) when a reversal of the changes caused by the previous low tide occurred. All these changes, though coincident with tidal movements, were no doubt dependent upon the fact that a bay is subject to greater diurnal changes than the open ocean. Water passing the collecting stations, especially that of series A, may be regarded as bay water during ebbing tide and as open sea water during flowing tide.

The temperature changes, then, may be explained by assuming that the water of the bay was cooled more rapidly during the night

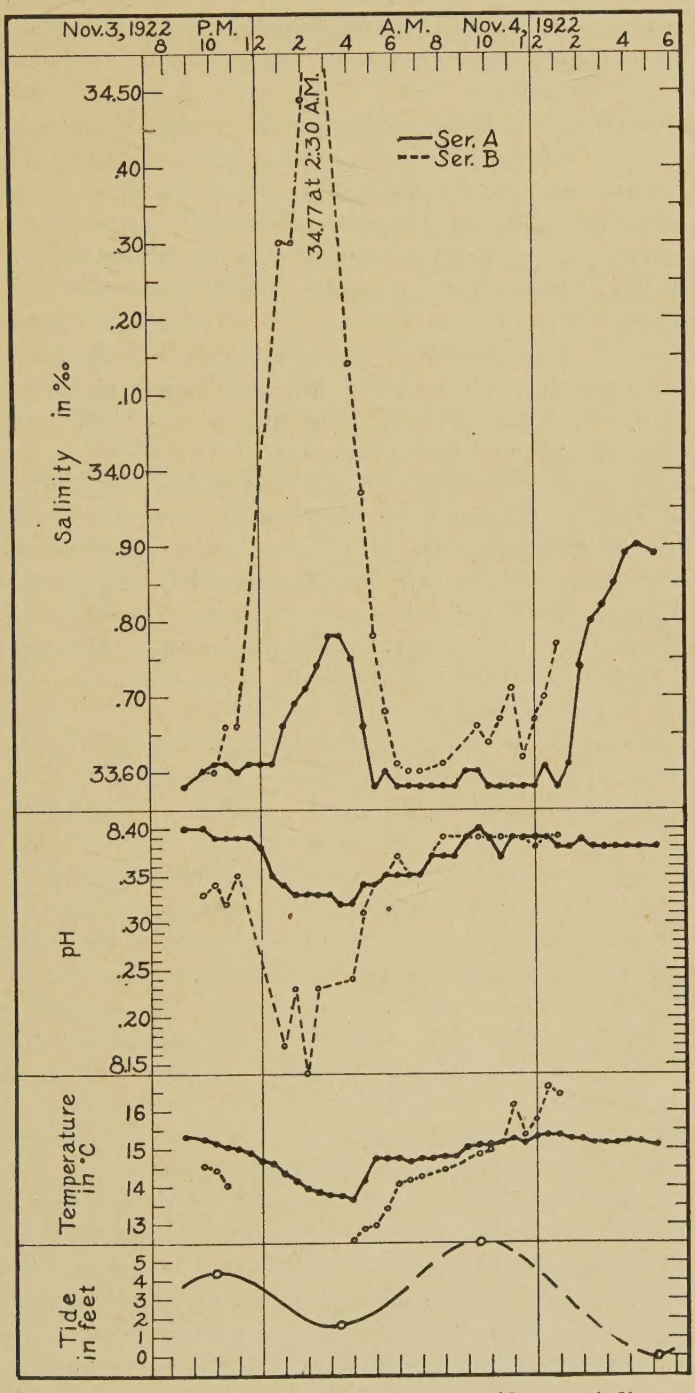

Fig. 1. Giving data for series A and B. Broken tide-curve indicates time between sunrise and sunset.

and heated more rapidly during the day than was the deeper offshore water. The heating effect was especially noticeable at the series B station.

The variations in H-ion concentration, which, of course, is not directly subject to solar influence, are less readily explained. Though the pH curves are roughly parallel to the temperature curves, the direct effect of temperature, which theoretically affects the degree of ionization, can be eliminated at once because at the time the pH readings were made all the samples were of practically the same temperature. It is certain that this fact introduced no error since experiments here and elsewhere (Cameron and Mounce, 1922) have shown that sea water in a tightly closed container may be heated or cooled several degrees without producing a measurable change in pH. Also, the rise in temperature of series B of over 1° at noon was not associated with a rise in pH. The H-ion concentration may also be affected by changes in the base content of the water. The rise in salinity occurring at ebbing tide was no doubt associated with an increase in base; but this increase was necessarily small and should have caused a rise in pH, whereas a decrease was observed. Most of the changes in the H-ion content probably resulted from variations in the quantity of carbon dioxide in the water. If this assumption is correct, it follows that the water contained more CO_2 during the night than during the day. This appears probable and might have been due to (1) absorption of CO_2 from the atmosphere, (2) increased production of CO_2 in the water, or (3) greater retention of the CO_2 produced. Since nothing is known concerning the CO_2 tensions of the bay water or of the overlying atmosphere, it is impossible to state what effect the observed temperature changes had upon the equilibrium between the CO_2 content of the air and of the water, but it is not likely that any CO_2 was absorbed from the atmosphere. The second possible explanation of the increase in CO_2 at night agrees well with the facts of plant and animal metabolism according to which the net production of CO_2 is smaller, or even negative, during the day. However, if the increase in CO_2, and the consequent lowering of pH, were caused by the activity of the plankton organisms, a similar change should have been evidenced by the water from the open ocean also, but the rise in pH to normal values with flowing tide indicates that practically no change took place. Moreover, a large number of pH determinations, made on many occasions, on water from the open ocean have failed to reveal any marked variations in pH that could definitely be correlated with photosynthetic activity, except during periods of the greatest phytoplankton yield. It is probable, therefore, that the indicated greater production of CO_2 in

the bay was due to the decomposition of the organic material which forms a layer of considerable thickness on the bottom of the bay. This decomposition probably took place at about the same rate night and day, but when the temperature was lowered the water was able to retain more CO_2.

The higher salinity of the water from the bay had been expected since conditions in the bay favor rapid evaporation and no fresh water had entered for some months. The greater increase in salinity during the afternoon ebbing tide was not necessarily due to greater evaporation at the time, but probably to the fact that the water reached a lower level than on the previous low tide, which would cause a larger proportion of stagnant bay water to reach the collecting stations.

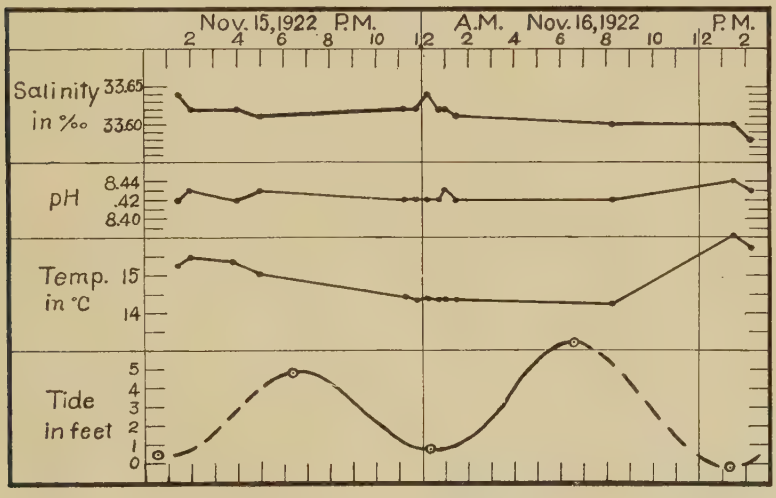

Fig. 2. Giving data for series C. Broken tide-curve indicates time between sunrise and sunset.

Series C

Series C was collected at the Scripps Institution pier, beginning about 2 P.M. on November 15, 1922, and continuing for about twenty-four hours. Since it was intended to determine whether the character of the water at low tide varied according to the time of the day, as had been the case at Mission Bay, observations were taken chiefly at the low tides. These coincided approximately with the periods when the results of diurnal effects should have been at a maximum or a minimum. Since the sky was clear and the water smooth, the conditions for producing marked diurnal changes were favorable.

The graph showing the results (fig. 2) indicates that the temperature began to fall shortly after 2 P.M. and continued to fall until the following morning. The rise during the morning and early afternoon of November 16 was no doubt caused by the sun's action and was independent of the tide.

Salinity and pH may be regarded as constant throughout the period. The variations were slight and practically within the limits of accuracy of the methods of determination.

Series D

Series D, collected at the Scripps Institution pier, was begun at 8 P.M. on August 23, 1923, and continued over a period of twenty-eight hours. Samples were taken from both the surface and the bottom, usually every half-hour. The results are shown in figure 3. The curve representing the current is not explained in the figure but is drawn so that zero tide on the graph equals absence of current (in a north or south direction) while points above this line represent various velocities in a southerly direction.

The temperature variations at the surface were slight and (with the exception of the sudden change about midnight of August 23) were apparently diurnal changes. From the beginning of the series, in the evening following a clear, warm day, there was a slow but continuous reduction in temperature which continued until 6:30 the following morning, when the temperature reached 0.6° below that of the first observation. On August 24 the sky was overcast and there was a cool northwest breeze blowing. Consequently there was no warming of the water until about 10 o'clock, when there was a rise of 0.3°, which persisted until about 2 P.M. only. The temperature changes, then, were evidently independent of tidal movements.

Neither pH nor salinity at the surface, though both very irregular, showed any definite trend that could be correlated with either tidal or diurnal conditions.

Temperature, pH, and salinity at the bottom were more variable and usually, though not always, lower than at the surface. The graph shows that during the first ten hours of the series there was a decided difference between the water from the surface and the bottom and that the flow of current was relatively slight. During the next fourteen hours, approximately corresponding to the period of daylight, the velocity of the current increased considerably and the water showed practically no gradient, while toward the end of the series the conditions prevailing at the beginning became reestablished. The

data are not complete, so that definite conclusions are not warranted, but a certain relationship between currents and the character of the bottom water is indicated. Since the current meter gave no information concerning current components not parallel to the coast, it is possible that the recorded weak current was in reality a strong current from an offshore direction. The offshore component of such a current

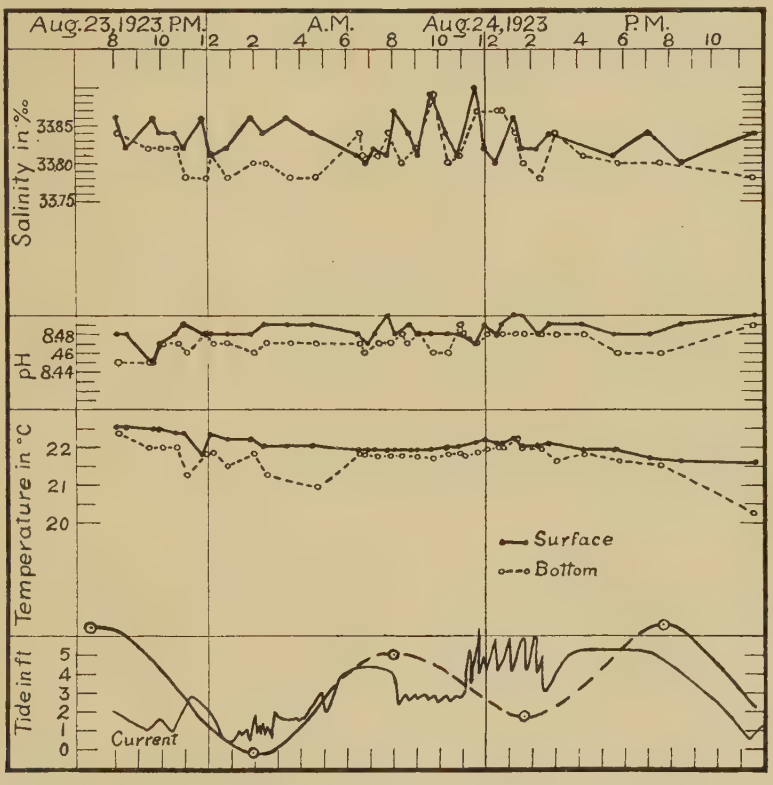

Fig. 3. Giving data for series D. Broken tide-curve indicates time between sunrise and sunset. For explanation of current see p. 8.

might have been merely the tidal flow, though in this series the height of the tide seemed to have no definite relation to the apparent velocity of the current. At any rate, a current flowing inshore would, upon entering the shallow areas, tend to force water from deeper strata toward the surface. Water coming from a depth of ten or twenty meters would differ from the surface water in regard to all the properties with which we were concerned and would account for the changes shown by the bottom water of this series.

Series E

Series E was collected according to the plan followed for series D except that samples were taken with greater regularity, every half-hour or oftener. The work was begun about 9 A.M. on September 9, 1923, and continued through the 10th, the day of the solar eclipse, until 4 P.M., September 11, or through a period of 55 hours. The results are shown in figure 4. In this case the curve representing currents is plotted so that no current coincides with the two-foot tide. Points above this line represent southerly flowing, and those below northerly flowing currents.

Even a cursory examination of the graph reveals several striking differences between the first and the last half of the series. These differences no doubt resulted, directly or indirectly, from similar differences in atmospheric conditions. During the first fifteen hours of the series the weather was clear and calm, but during the remainder it was cloudy and an inshore breeze caused the sea to become choppy. The dependence of hydrographic conditions upon atmospheric conditions was suggested by the fluctuations of the temperature at the surface. During the first part of the series the temperature showed changes that were typically diurnal, whereas during the latter part, after the change in weather conditions had taken place, it remained practically constant.[1]

In the case of pH there were numerous minor irregularities, ranging from pH 0.01 to 0.03, which made the larger fluctuations somewhat obscure. Nevertheless, it may be stated that, in general, pH resembled temperature in that at the beginning of the series it changed according to the time of day and that later there were no significant changes.

Salinity was also irregular, and diurnal changes were even less obvious than in case of pH. During most of the series it showed a slight upward trend, probably due to the fact that the temperature remained rather high. The most striking changes in the character of the water took place at the bottom. This was most noticeable in respect to temperature. During a period of three or four hours at each low tide, the surface and bottom temperatures were practically identical, but soon after the water began to rise the temperature at the bottom fell rapidly and, after remaining at a more or less constant low level for several hours, rose with equal abruptness a few hours after high tide. It is perhaps significant that during the first part of the series the periods of low bottom temperature were of longer

[1] The sudden drop in surface temperature about 5 A.M. on September 10 was probably due to eddy currents.

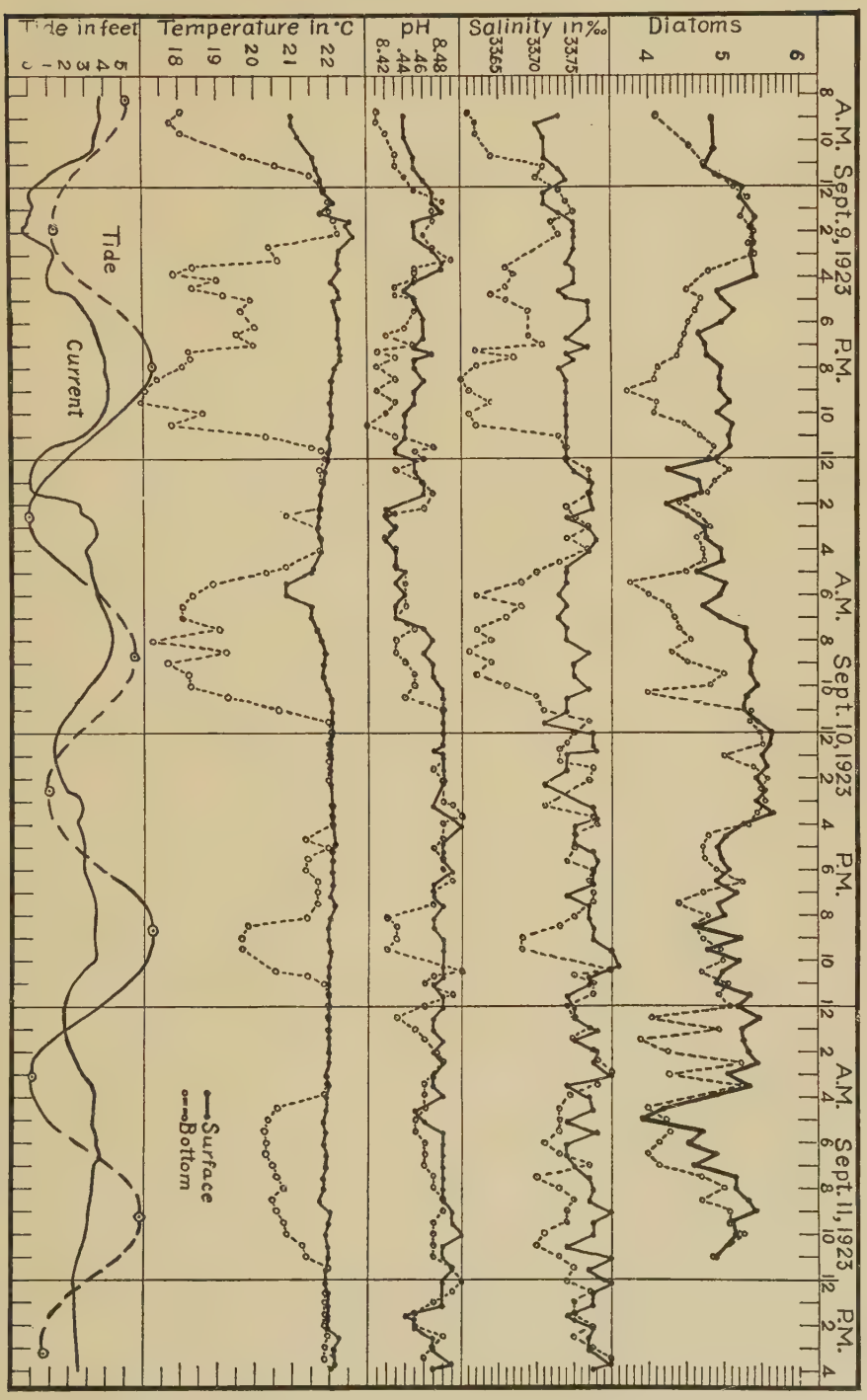

Fig. 4. Giving data for series E. Broken tide-curve indicates time between sunrise and sunset. For explanation of current see p. 10. The diatom curve represents logarithms of the number of diatoms per liter.

duration and the differences between surface and bottom temperatures greater than during the latter part. After the first low tide of the series the temperature at the bottom reached a value of 5° below that at the surface, but after the last low tide the maximum difference was only about 1.5°.

Variations in pH and salinity at the bottom were similar to those in temperature, but were relatively smaller and are not so plainly shown on the graph, due to irregularities at the surface. At low tide, pH and salinity values at the bottom equaled, or even exceeded, those at the surface, but on rising tide the values decreased by pH 0.03 or 0.04, and by 0.10‰ to 0.15‰, respectively.

The results leave no doubt that at the bottom there was a strong parallelism in the three conditions investigated. It is highly improbable, however, that a direct causal relation existed, and it seems safe to conclude that they were all controlled by a common cause or combination of causes. With respect to time the fluctuations in the character of the bottom water were practically coincident with tidal changes and, at first glance, one would suppose that tide was the determining factor. This view, however, is not supported by the results of series D nor does it explain the decreasing range of fluctuations of this series. The fact that during the latter part of the series the water was agitated does not afford an explanation of the decreasing range since, had the bottom water been affected by an admixture of surface water, there should have been a reciprocal change at the surface, and there was not.

It seems highly probable that currents were the most immediate cause of the phenomena observed. The graph shows that on each of the five occasions when the bottom water began to show a difference from the surface water there was a fairly abrupt change in the current. A similar change, but in an opposite direction, occurred each time the difference began to disappear. During the first part of the series currents were stronger and reversals more abrupt than during the latter part. This affords a reasonable explanation of the diminishing variability of the bottom water toward the end of the series. It should be stated that in the case of this series a southerly flowing current was associated with low temperature, pH, and salinity at the bottom, whereas with series D the opposite was true. In each case, however, a change in the velocity and direction of the current brought about a change in the hydrographic conditions of the water, probably by producing a change in the amount of deeper offshore water brought toward the shore.

On the other hand, it is quite evident that, during this series at least, currents were affected by tidal movements to a considerable

extent and it is very probable that weather conditions, especially the direction and velocity of the wind, were responsible for the difference between the two parts of the series with respect to currents. Other factors, which certainly must influence the conditions near shore but concerning which we have no detailed information, are the larger offshore currents, both vertical and horizonal. It is probable that these, together with tidal movements and wind conditions, are largely responsible for the local water currents observed at the pier.

SUMMARY

The results of these series indicate that, in the San Diego region, there is no uniformity in the effects produced by tidal movements upon temperature, hydrogen ion concentration, and salinity of sea water near shore. In a shallow bay there may be marked changes in the character of the water, at least during certain seasons and conditions of the atmosphere. Along the open coast the surface water may remain practically unchanged over long periods of time and such fluctuations as do occur are apparently not related to tidal movements. At the bottom, however, pronounced variations often take place. At times these coincide with tidal changes but at other times there is no evident relationship. It seems safe to conclude that fluctuations in the physical and chemical conditions of sea water result from numerous causes, some of which, such as currents, may be influenced by tidal movements. It can also be stated that no great reliance should be placed upon a single determination of any property of sea water, especially near shore, since sudden, sometimes considerable, changes often take place.

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II. HALF-HOURLY COLLECTIONS OF MARINE MICROPLANKTON TAKEN AT THE SCRIPPS INSTITUTION PIER IN 1923

BY

WINFRED EMORY ALLEN

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INTRODUCTION

The present discussion deals only with diatoms and dinoflagellates of the microplankton collected in series E (see p. 10). Unfortunately, with neither group was the time (solar eclipse of 1923) favorable for this type of study. Productivity was rather low and typical representatives of the true plankton were few. In spite of these objectionable conditions it seems desirable to make this study a matter of record, and to call attention to certain points which require further investigation.

Moberg's figure 4 (p. 11) shows the variations in diatoms and in physical and chemical conditions examined from shortly after high tide in the forenoon of September 9 to high tide in the forenoon of September 11.

DIATOMS

Most of the diatoms in these catches were very small. By far the largest numbers belonged to unidentified species of the genus *Chaetoceras,* in which specific characters are very obscure and difficult to recognize. Most of these appeared to belong to *C. compressum* Laud. but some other small species may have been included. The individual cells were so small as to be difficult to distinguish at the magnification necessarily used for enumeration. In nearly all catches this assemblage contributed from 70 to 90 per cent of the total numbers of diatoms. About 10 to 20 per cent (varying in different catches)

consisted of a small naviculoid species, probably *Navicula lacustris* (Ag.), which is common on the piling and submerged structures about the pier. Other species were too few in number to have significance in a short-time study.

It is very interesting to note that at both bottom and surface the numbers of diatoms tended to increase with ebbing tide and to decrease with flowing tide (fig. 4). Whether this is correlational or merely incidental can be determined only by extensive work along similar lines. The fact that, at the bottom there is also strong indication of similar trends (fig. 4 and p. 8) in salinity, pH, and temperature (to say nothing of the lesser similarity at the surface), gives considerable reason for inclining to the view that such a correlation actually existed.

Granting such a correlation, how is it to be explained? If the naviculoid species played a larger part in the showing of diatoms, one might plausibly suggest that at lowering tide increasing numbers were exposed to breaker action and so dislodged from growing points on the piling near the place of collecting. But their numbers are surely too small to be so accounted for. The only other explanation which occurs to me is that diatoms, as well as larger particles of material passive in the water, tend to concentrate or accumulate along shore in response to tidal action, and, with a smooth sea, would tend also to settle on such a shelf as this about the pier in shallow water beyond the breakers. With ebbing tide the action of the breakers would take place much farther out from shore and would, doubtless, stir up more diatoms, just as it stirs up more of other fine sediments from the bottom near the end of the pier.

It is true that this supposition is weakened by the discordant showings of surface and bottom at the second and third high tides, but that discordance is largely offset by the fact that the sea was relatively calm through the first two ebbing, and the first two flowing, tides and relatively agitated through much of the remaining part of the collecting period. That is to say, the greater general agitation of the sea at the later time obliterated the differences coincident with tidal movements and caused a more nearly uniform distribution of diatoms through the water.

As shown very strikingly by the graph (fig. 4), changes in number are much more abrupt and of greater range for the bottom than for the surface catches. This indication of greater stability of surface conditions is probably peculiar to shallow inshore water, where the topography, both of the bottom and the shore line, exerts confusing influences.

DINOFLAGELLATES

The species of dinoflagellates represented in the catches were mostly pelagic forms typical of the region but they were present in very small numbers, the total being less than 2,000 to the liter in 90 per cent of the catches. A careful examination of a graph and table showing their distribution failed to reveal any prominent points. While they did not correspond with the showing of diatoms, they did not give ground for altering previous conclusions. *Ceratium furca* (Ehr.) Duj., *Dinophysis homunculus* Stein, *Peridinium divergens* Ehr., and *P. pyriforme* Pauls. were the more prominent species represented.

CONCLUSION

So far as it goes, the evidence of series E indicates a general probability that larger catches of diatoms and dinoflagellates may be obtained on open sloping shores as the tide ebbs.

The exact relationships are too intricate for present interpretation but it does seem clear that the ordinary ranges of change of the easily accessible factors in the environment of a particular inshore locality are not great enough to establish short-term correlations with the fluctuations in populations of diatoms and dinoflagellates. They are mainly coincidental in response to inshore movements of the water masses.

As might be expected in such passive biological material there was no evidence of any effect of the total eclipse of the sun.

This series affords some interesting points for comparison with the Mission Bay series (Moberg, series A). Especially worth noting is the fact that, as the tide ebbed, catches increased at the pier, instead of diminishing as at Mission Bay. The two series (A and E) together have disclosed some definite problems and suggested a field for an unlimited amount of intensive study of inshore conditions of plankton production.

Not the least of the value of the pier series is the warning which it affords of need of caution in interpreting short-period or limited evidence. If the series had covered only the first day the correlations would have appeared to be remarkably clear and positive, whereas the second day showed that they were very readily disturbed and obscured, if not obliterated, by changes in movements of large masses of water.